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An Evaluation of Effective Radiuses of Bulk-Wave Ultrasonic Transducers as Circular Piston Sources for Accurate Velocity Measurements

Mototaka Arakawa, *Member, IEEE*, Jun-ichi Kushibiki, *Member, IEEE*, and Naoya Aoki

***Abstract*—The effective radius of a bulk-wave ultrasonic transducer as a circular piston source, fabricated on one end of a synthetic silica (SiO_2) glass buffer rod, was evaluated for accurate velocity measurements of dispersive specimens over a wide frequency range. The effective radius was determined by comparing measured and calculated phase variations due to diffraction in an ultrasonic transmission line of the SiO_2 buffer rod/water-couplant/SiO_2 standard specimen, using radio-frequency (RF) tone burst ultrasonic waves. Fourteen devices with different device parameters were evaluated. The velocities of the nondispersive standard specimen (C-7940) were found to be 5934.10 ± 0.35 m/s at 70 to 290 MHz, after diffraction correction using the nominal radius (0.75 mm) for an ultrasonic device with an operating center frequency of about 400 MHz. Corrected velocities were more accurately found to be 5934.15 ± 0.03 m/s by using the effective radius (0.780 mm) for the diffraction correction. Bulk-wave ultrasonic devices calibrated by this experimental procedure enable conducting extremely accurate velocity dispersion measurements.**

I. Introduction

In ultrasonic metrology used for studying physical properties and characterizing materials, it is extremely important to measure acoustic properties of velocity-dispersive specimens over a wide frequency range. We have developed an ultrasonic spectroscopy system for accurately measuring these acoustic properties (viz., phase velocity and attenuation) of solid, liquid, and biological tissue specimens in the very high frequency (VHF) and ultra high frequency (UHF) ranges [1]. The measurements were conducted using radio-frequency (RF) tone burst ultrasonic pulses with ultrasonic devices consisting of synthetic silica (SiO_2) glass buffer rods and bulk-wave transducers fabricated on one end of an ultrasonic transmission line (Fig. 1).

One cause of errors in measuring the acoustic properties is the effect of phase variation due to diffraction. Extensive analyses and calculations of ultrasonic losses and phase advances due to diffraction have been conducted [2]–[6]. Various attempts also have been made to detect them through experiments [6]–[9]. We have been attempting to detect experimentally the diffraction effects in the VHF range and to develop correction methods for them for more precisely measuring sound velocity at higher frequencies [10]. We also have developed a complex-mode measurement method [10] and a general measurement method for dispersive specimens [11], and we successfully have obtained detailed information on velocity dispersion useful for materials research.

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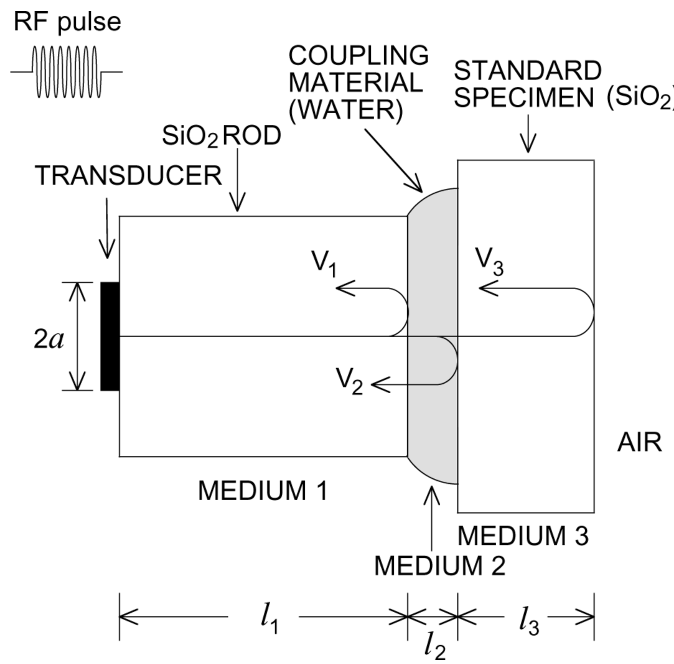

Fig. 1. Experimental arrangement for evaluating effective radius of a bulk-wave ultrasonic transducer as a circular piston source using a standard plate specimen (SiO_2).

However, at lower frequencies, in which the diffraction effect is larger, considerable variations in velocity are occasionally observed, even after correction. This may be because the parameters used to calculate numerically the diffraction effect differ from the real ones, so that the diffraction effect is not completely corrected. Of all the parameters used for the calculations, an error in the circular transducer radius most affects the calculated values. Therefore, it is very important that the effective radius of the transducer is ascertained.

In the experiment reported in this paper, the effective radiuses of bulk-wave ultrasonic transducers as circular piston sources are evaluated, using SiO_2 glass specimens as standard solid specimens. These specimens are isotropic solids with well-known sound velocity and small losses, and no velocity dispersion in the VHF range. In the evaluations, phase variations due to diffraction are measured for the standard specimens, and the obtained values are compared with calculated values. Their effectiveness in velocity measurements also is investigated.

II. Experiments

A. Method and System

Fig. 1 illustrates the experimental arrangement used for evaluating the effective radius of a bulk-wave ultrasonic transducer as a circular piston source. This arrangement is the same as that used for the velocity measurements of solid specimens [10]. Measurements of phase variations due to diffraction were carried out by measuring the amplitude and phase of RF tone burst signals using the complex-mode measurement method [10]. Pure water was used for the couplant.

The reflected signals from the front and back surfaces of the specimen, $\mathbf{V}_2$ and $\mathbf{V}_3$, were measured, the phase rotation ϕ was extracted by normalizing $\mathbf{V}_3$ by $\mathbf{V}_2$, and it is expressed as follows [10]:

$$\phi = -2k_3 l_3 + \pi + \Delta\theta, \tag{1}$$

where $-2k_3l_3$ is the phase rotation in the standard specimen, k_3 is the wave number, and l_3 is the propagation length of the specimen. In (1), $\Delta\theta$ is the difference in phase advance due to diffraction, defined by $\Delta\theta = \theta_3 - \theta_2$, where $\theta_2(\theta_3)$ is the phase variation for the diffraction effect during the propagation of signal $\mathbf{V}_2$ ($\mathbf{V}_3$), $ATT_{2(3)}$, that is expressed as:

$$ATT_{2(3)} = \left|ATT_{2(3)}\right| \exp\left(j\theta_{2(3)}\right). \tag{2}$$

As the phase velocity is ω/k (ω: the angular frequency), the sound velocity V of the standard specimen can be expressed using ϕ in (1) by:

$$V = -\frac{2\omega l_3}{\phi - \pi - \Delta\theta}, \tag{3}$$

where V includes $\Delta\theta$ so that its effect has to be corrected.

Experimental $\Delta\theta$ is obtained by subtracting the phase rotation in the standard specimen ($-2k_3l_3$) and π from the measured ϕ, as the phase velocity of the standard specimen already has been determined with high accuracy.

Theoretical $\Delta\theta$ due to diffraction can be calculated numerically using the exact integral expression of diffraction by Williams [2]. In these measurements, ultrasonic waves are propagated through different media. In order to calculate θ_2 and θ_3, the sums of the propagation length $S(= l/l_F)$ of each medium normalized by the Fresnel length $l_F(= a^2/\lambda$, where λ is the wavelength and a is the transducer radius) were calculated based on the Papadakis method [12] and were substituted into the Williams expression. The validity of this method on accurate measurements of velocity and attenuation coefficient was verified experimentally in the previous paper [10].

Diffraction effects in velocity measurements cannot be corrected completely when one or more of the parameters used for numerical calculations (e.g., the transducer radius, the velocities in the media, and the propagation distances of the media) differ from the real values. The error in the propagation distance of each medium is very small because it is possible to measure each propagation distance accurately. Differences in acoustic properties due to different production lots of SiO_2 buffer rods can cause errors. However, the effects of these differences are considered to be at most about 0.2%, which is a negligible contribution to such variations [13], [14]. The velocity in water was obtained from the literature [15], referring to the water couplant temperature in the measurement. However, it is very difficult to accurately estimate the radius of the fabricated ultrasonic transducer and the practical situation of the sound source. Thus, we deduced that inaccuracy in the transducer radius affects phase variations due to diffraction the most and concluded that the effective radius of the transducer as a circular piston source must be obtained. So, an effective radius for the transducer fabricated can be obtained through the numerical calculations of a theoretical $\Delta\theta$ curve as a function of frequency that coincides with a measured $\Delta\theta$ curve.

Measurements were made with an ultrasonic spectroscopy system [1], [10]. The entire system was installed in a temperature-controlled room, in which the temperature was maintained within ±0.1°C because temperature stability plays an important role in the measurements.

The measurements are made in the reflection mode in the composite ultrasonic transmission line as shown in Fig. 1. Unlike measurements in the transmission mode, many multiple reflection and transmission signals are generated in the time domain, most of which are spurious signals [10]. As a result, it is necessary to adjust the width of RF pulses, the rod length, the propagation length in the water couplant, and the thickness of the specimen to appropriate values so that the signals $\mathbf{V}_2$ and $\mathbf{V}_3$ do not overlap with the spurious signals.

B. Ultrasonic Devices and Standard Specimens

Table I lists the specifications of longitudinal ultrasonic devices evaluated. Most of the transducers were made of piezoelectric zinc oxide (ZnO) films fabricated by the direct current (DC) sputtering method. These transducers were formed by sandwiching the ZnO films with Cr-Au-film top and bottom electrodes, having the same dimensions of circular electrodes and lead pads, by the vacuum-evaporation technique. Lead wires were bonded to the lead pads, and the overlapped circular electrode areas were driven as an ultrasonic transducer. One transducer (Device No. 1), operating at lower frequencies, used a 36°Y-

TABLE I
Parameters of Longitudinal-Wave Ultrasonic Devices, and Designed and Effective Radiuses of Circular Transducers.

Device No.	Center freq. (MHz)	Rod length (mm)	Transducer material	Transducer radius (mm)	
				Designed	Effective
1	71	7.84	36°Y-cut $LiNbO_3$	2.50	2.539
2	100	14.0789	ZnO	1.50	1.514
3	141	9.9835	ZnO	1.00	1.011
4	150	8.0226	ZnO	1.25	1.264
5	150	8.0346	ZnO	1.25	1.277
6	187	14.0621	ZnO	1.50	1.515
7	196	8.0225	ZnO	0.75	0.758
8	196	9.9827	ZnO	1.25	1.262
9	210	11.9479	ZnO	1.25	1.254
10	280	8.0348	ZnO	1.25	1.265
11	282	9.9838	ZnO	1.00	1.009
12	399	8.0350	ZnO	0.75	0.780
13	420	8.0229	ZnO	0.65	0.650
14	420	8.0350	ZnO	0.65	0.666

TABLE II
Specifications of SiO_2 Glass Standard Specimens.

Standard specimen	Dimension	Velocity (m/s at 23°C)	Parallelism (second)
C-7940[1]	30 mm × 50 mm thickness: 2767.41 ± 0.06 μm	5934.08 ± 0.13	2.2
C-7980[1]	50 mm × 50 mm thickness: 4985.48 ± 0.06 μm	5929.14 ± 0.07	2.0

[1]Corning, Inc., Corning, NY.

cut $LiNbO_3$ plate transducer with a circular top electrode of nominal 2.50-mm radius that was bonded with a resin to the Cr-Au-film bottom electrode that was coated on the whole surface of one end of the SiO_2 buffer rod. One of two lead wires was bonded directly to the top electrode with a conductive silver paint. Fig. 2 shows the typical frequency characteristics of the insertion loss of Device No. 12. The lengths of the buffer rods were measured with a digital length-gauging system with an optical encoder (measurement accuracy of ± 0.06 μm) before the transducers were fabricated. During fabrication, desired sizes of the transducers were controlled by pattern sizes of metal masks when the electrodes were formed by the vacuum evaporation technique. The designed radiuses shown in Table I are the nominal radiuses of the patterns. Table II presents the specifications of the two SiO_2 standard specimens. The specimens were optically polished on both sides, and the effect of parallelism of the specimen surfaces on the velocity measurement was negligible at the frequencies used in these measurements. The errors in the velocities are at present dominated mainly by the accuracy of the plate thickness measurements (± 0.06 μm).

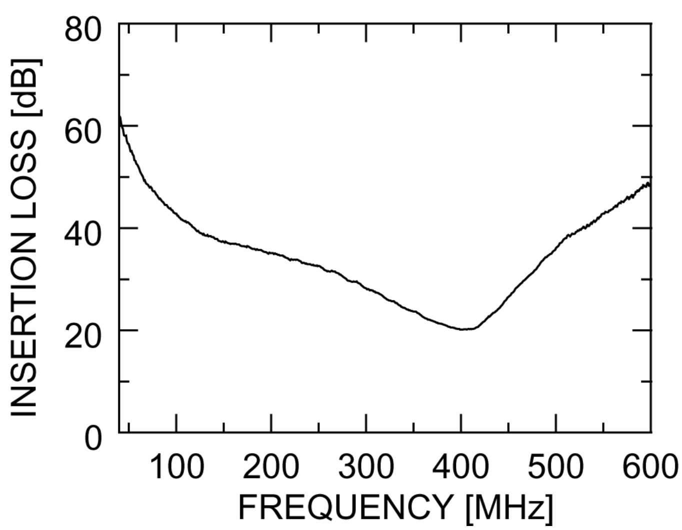

Fig. 2. Typical frequency characteristics of insertion loss of a plane-wave ultrasonic device (No. 12 in Table I) of a ZnO film transducer fabricated on an 8-mm-long SiO_2 buffer rod. ZnO film thickness = 5.5 μm, transducer diameter = 1.5 mm.

C. Results

As an example, the evaluation procedures for Device No. 12 are shown using the nondispersive C-7940 standard specimen in the VHF range. The propagation length in the water couplant was 936 μm, and the measurement temperature was 23.01°C. The phase of $\mathbf{V}_3/\mathbf{V}_2$, ϕ, was obtained in Fig. 3, and the phase rotation in the specimen and π were subtracted from the obtained phase, in order to extract $\Delta\theta$. The solid line in Fig. 4 represents the result. These values then were compared with those

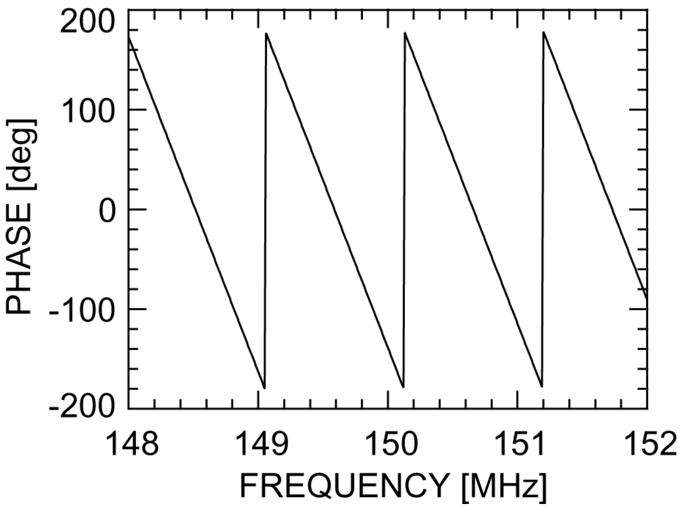

Fig. 3. An example of frequency response of phase of $\mathbf{V}_3/\mathbf{V}_2$ measured for the C-7940 standard specimen (2767.41-μm thick).

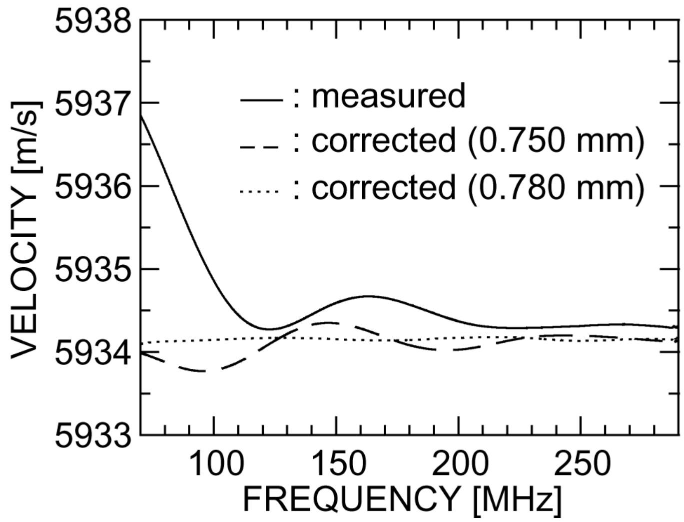

Fig. 5. Measured and corrected velocities for the C-7940 standard specimen. Diffraction corrections were made with a = 0.750 and 0.780 mm.

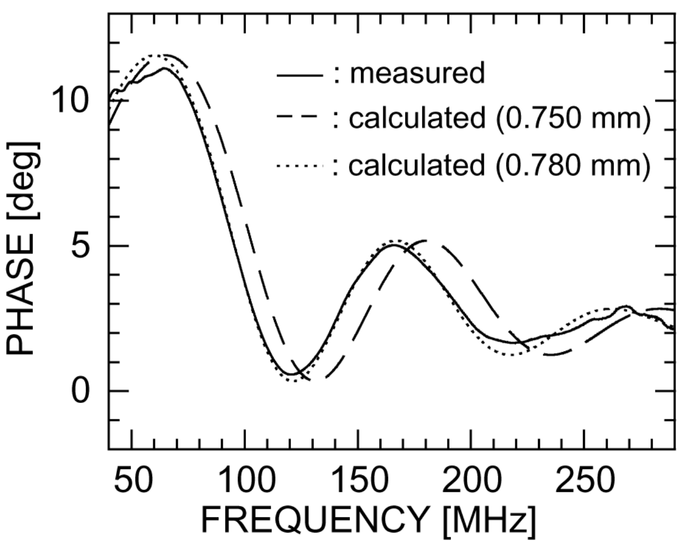

Fig. 4. Measured and calculated phase advance difference $\Delta\theta$ for the C-7940 specimen using Device No. 12. Calculations were made with $a = 0.750$ and 0.780 mm.

obtained through numerical calculations. The calculations were performed with a transducer radius of the designed value ($a = 0.75$ mm) established when the device was fabricated, as given by the broken line in Fig. 4, along with the measured values. They were found to differ remarkably. To understand the effect of the radius on the numerical calculations for the ultrasonic device, the calculations of $\Delta\theta$ also were carried out with other different transducer radiuses of a = 0.70 (0.80) mm. In the results, the calculated $\Delta\theta$ curves shift toward lower frequencies as the transducer radius increases. The pattern of the measured results is located at lower frequencies than that of the calculated results for the nominal radius of a = 0.750 mm in Fig. 4, the effective transducer radius is expected to be larger than the designed radius. Next, $\Delta\theta$ was numerically calculated using a parameter of transducer radius. A proper, effective radius can be obtained by examining the difference $\Delta\theta$ (measured) $-$ $\Delta\theta$ (calculated) as a function of frequency. A parabolic approximation was made for the standard deviations of the differences plotted against the transducer radiuses. The radius at the bottom of the parabola ($a = 0.780$ mm) was estimated to be the effective radius of the transducer.

The calculated values of phase variations caused by diffraction using the effective transducer radius are presented by the dotted line in Fig. 4. There was excellent agreement, in contrast with the results for the nominal radius. The other 13 devices were evaluated similarly, and the results are summarized in Table I. All the devices were measured in the temperature range of 23.00 ± 0.11°C. The effective radiuses became larger than the designed radiuses by 0–4%. These were mainly caused by the problems associated with the device fabrication process and conditions, that is, the different actual radiuses of top/bottom electrodes from the designed radiuses and the different overlapping areas between the top and bottom electrodes.

Fig. 5 shows the velocities measured for the C-7940 standard specimen using Device No. 12. The solid line represents the velocities with the diffraction effect ignored; the broken (dotted) line represents the velocities with diffraction corrections using the designed (effective) transducer radius. The measured values were remarkably large due to diffraction, especially at lower frequencies. Furthermore, the measured velocities exhibit very small variations at frequencies above 231 MHz, where S equals unity. By correcting the diffraction effect using the designed transducer radius of 0.75 mm, nearly constant velocity values (5934.17 ± 0.06 m/s) were obtained at the frequencies (231 to 290 MHz) where $S < 1$; but some variations still existed at the lower frequencies, yielding 5934.10 ± 0.35 m/s at 70 to 290 MHz. By correcting the diffraction effects using the effective transducer radius (0.780 mm), velocity values of 5934.15 ± 0.03 m/s were obtained at 70 to 290 MHz,

TABLE III
Corrected Velocities of the Standard Specimens Using the Designed and Effective Radiuses of Circular Transducers.

Device No.	Center freq. (MHz)	Frequency range (MHz)	Corrected velocity (m/s)		Standard specimen
			Designed	Effective	
1	71	30 − 90	5934.08 ± 0.07	5934.09 ± 0.06	C-7940
2	100	60 − 150	5934.09 ± 0.12	5934.09 ± 0.10	C-7940
3	141	80 − 210	5929.08 ± 0.11	5929.08 ± 0.03	C-7980
4	150	70 − 200	5933.99 ± 0.12	5934.00 ± 0.09	C-7940
5	150	50 − 210	5934.08 ± 0.14	5934.08 ± 0.06	C-7940
6	187	60 − 240	5934.14 ± 0.12	5934.14 ± 0.09	C-7940
7	196	60 − 260	5934.00 ± 0.14	5934.02 ± 0.11	C-7940
8	196	50 − 230	5929.14 ± 0.10	5929.14 ± 0.03	C-7980
9	210	60 − 270	5929.04 ± 0.12	5929.04 ± 0.10	C-7980
10	280	50 − 310	5934.11 ± 0.08	5934.12 ± 0.05	C-7940
11	282	60 − 300	5929.12 ± 0.11	5929.13 ± 0.05	C-7980
12	399	70 − 290	5934.10 ± 0.35	5934.15 ± 0.03	C-7940
13	420	90 − 280	5934.02 ± 0.03	5934.02 ± 0.03	C-7940
14	420	90 − 280	5934.01 ± 0.14	5934.06 ± 0.07	C-7940

although the average value of 5934.15 m/s was slightly (+0.07 m/s) different from the true value of 5934.08 m/s for the C-7940 standard specimen. These results reveal that velocity variations decrease when diffraction is corrected using the effective radius of the transducer.

Similarly, velocities for SiO_2 standard specimens using the other 13 devices were determined and are summarized in Table III, in which the velocities were corrected at 23.00°C using the temperature coefficient of the longitudinal wave velocity of SiO_2 [13].

III. Discussion

As Table III demonstrates, obtaining the effective transducer radius for each device reduced variations in velocity to some degree, although the effectiveness was significant for Device No. 12 that had a relatively large difference between the nominal and effective radiuses (4%). This finding is very useful for accurately measuring velocity dispersion of dispersive specimens. In addition, a velocity difference of approximately 5 m/s was observed between the two standard specimens used here. This probably is caused by differences in impurity densities introduced [14] or by different heat histories [16], [17] during the fabrication processes.

As shown in Fig. 6, large differences were observed between the measured and calculated phase variations due to diffractions obtained for Device No. 1. Only Device No. 1 had the lead line for conduction fixed to the top electrode surface of the transducer with a silver conductive paint. When the transducer excites ultrasonic waves, the lead line and conductive bonding material attaching it to the electrode act as an acoustical load, thus leading to the relatively large differences from the calculated values, which were calculated assuming that the ideal circular piston source was uniform. On the other devices, the electrodes protrude from the transducers and the leads are fixed to the extended pads, so there is no acoustical loading. However, even for Device No. 1, the diffraction correction using the effective radius of the transducer evaluated in the same procedure is very useful for accurate velocity measurements, as shown in Table III.

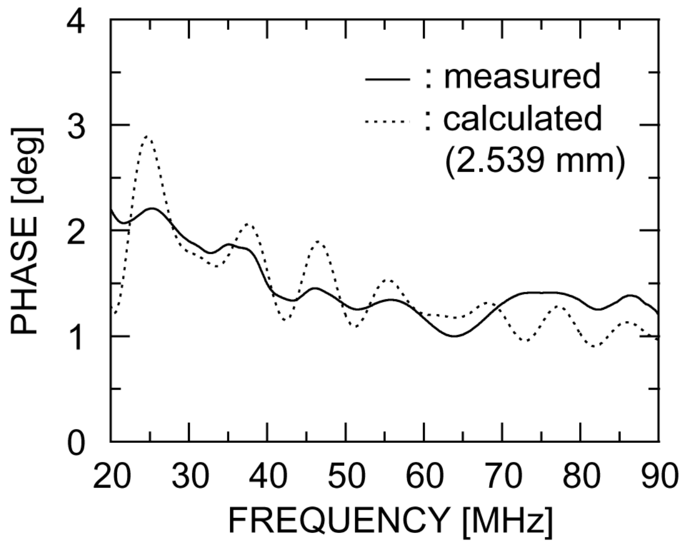

Fig. 6. Comparison of measured and calculated phase advance difference $\Delta\theta$ for the C-7940 specimen using Device No. 1. Calculations were made with $a = 2.539$ mm.

Device No. 12, which is taken as an example, has an operating center frequency of about 400 MHz. In these measurements, the propagation length of the water couplant was chosen to be 936 μm to ensure that the RF pulse width was sufficiently large. The attenuation of water increases significantly at higher frequencies, and the signal to noise ratio of the signals to be measured deteriorates at frequencies above 290 MHz because the attenuation coefficient of water increases proportionally to the square of the frequency [18]. This method (e.g., obtaining the effective radius and correcting the diffraction effect) enables us to measure velocities in a broad frequency range of 70 to 290 MHz, even though the frequency range of 231 to

290 MHz, where $S < 1$, is conventionally used for accurate velocity measurements.

IV. Conclusions

This paper evaluated the effective radiuses of ultrasonic bulk-wave transducers as circular piston sources. The effective radiuses were obtained by comparing measured and calculated values of phase variations due to diffraction, using SiO_2 glass specimens as the standard specimen in the measurement. It also was demonstrated that variations in velocity disappear when the diffraction effect is corrected using the effective transducer radiuses. The use of this method enables accurate velocity measurement in a wide range of frequencies and is especially useful in measuring velocity dispersion for dispersive specimens with a very high accuracy (five significant figures or more). In the future, our studies will investigate the effects of different effective radiuses of the transmitting and receiving transducers on velocity measurements in the transmission mode and the effects of the acoustic load on the sound source as seen for Device No. 1.

Acknowledgments

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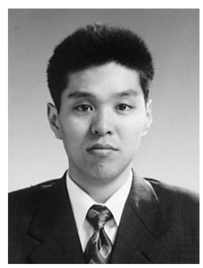

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Dr. Kushibiki is a Fellow of the Acoustical Society of America; a member of the Institute of Electronics, Information and Communication Engineers of Japan, of the Institute of Electrical Engineers of Japan, of the Acoustical Society of Japan, and of the Japan Society of Ultrasonics in Medicine.